

401 891

63-3-2

①

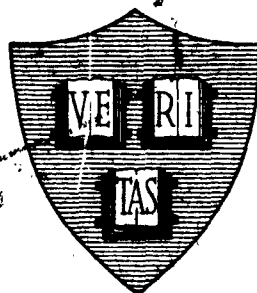
Office of Naval Research

Contract Nonr-1866 (32)

NR 371-016

A STUDY OF THE SLOT TRANSMISSION-LINE
AND SLOT ANTENNA

Part 1. Some Investigation of the Slot Transmission-Line



By

Robert W. Burton

January 10, 1963

Technical Report No. 397

Cruft Laboratory
Harvard University
Cambridge, Massachusetts



AD No. 401 891
ASTIA FILE COPY

\$ 2.60

Office of Naval Research

(12) Contract Nonr-1866(32), Prof. ↑
NR - 371 - 016

(1) Technical Report

(6) A STUDY OF
THE SLOT TRANSMISSION-LINE AND SLOT ANTENNA
Part 1. Some Investigation of the Slot Transmission-Line

by

(8)

Robert W. Burton

(9) 1 January (10) 1963

The research reported in this document was made possible through support extended Cruft Laboratory, Harvard University, jointly by the Navy Department (Office of Naval Research), the Signal Corps of the U. S. Army, and the U. S. Air Force, under ONR Contract Nonr-1866(32). Reproduction in whole or in part is permitted for any purpose of the United States Government.

(10) 10. incl.
illus. 4 refs.

(11) Technical Report No. 397

Cruft Laboratory

Harvard University

Cambridge, Massachusetts

(13) NA


(14) Uncl

(15) NA

(5) 234 300

42

Abstract

A series of related experiments on the slot transmission-line and their results are described. The three major phases of investigation are (a) a conducting image plane as a termination for a slot transmission-line, (b) a practical design of a matched load, (c) the effect of a bend-out-of-the-plane on the transmission characteristics of the slot transmission-line.

Page 1-8

1-0

A STUDY OF THE SLOT TRANSMISSION-LINE AND SLOT ANTENNAS

Part 1. Some Investigations of the Slot Transmission-Line

by

Robert W. Burton

Division of Engineering and Applied Physics

Harvard University, Cambridge, Massachusetts

1.1 Introduction

In 1959 G. Owyang demonstrated the slot transmission-line in experiments and supported his experimental evidence with a rigorous theory [1]. The slot transmission-line was fabricated by cutting two long slots in a large ground plane and employing the slots for transmission of energy much as one employs wires in normal transmission-line application. As is pointed out by Owyang, the transition from two-strip transmission-line theory to two-slot transmission-line theory in the plane is straightforward. A direct analogy between an electric strip and magnetic strip line may be drawn in all cases; and, in a plane the link between the magnetic strip and slot line is made by application of Babinet's principle. It is the purpose of this first study to investigate experimentally the effects encountered when a slot-transmission-line is employed out of the plane and to attempt to offer some direction in which a theory may be constructed.

Three phases of experiment are incorporated in this investigation:

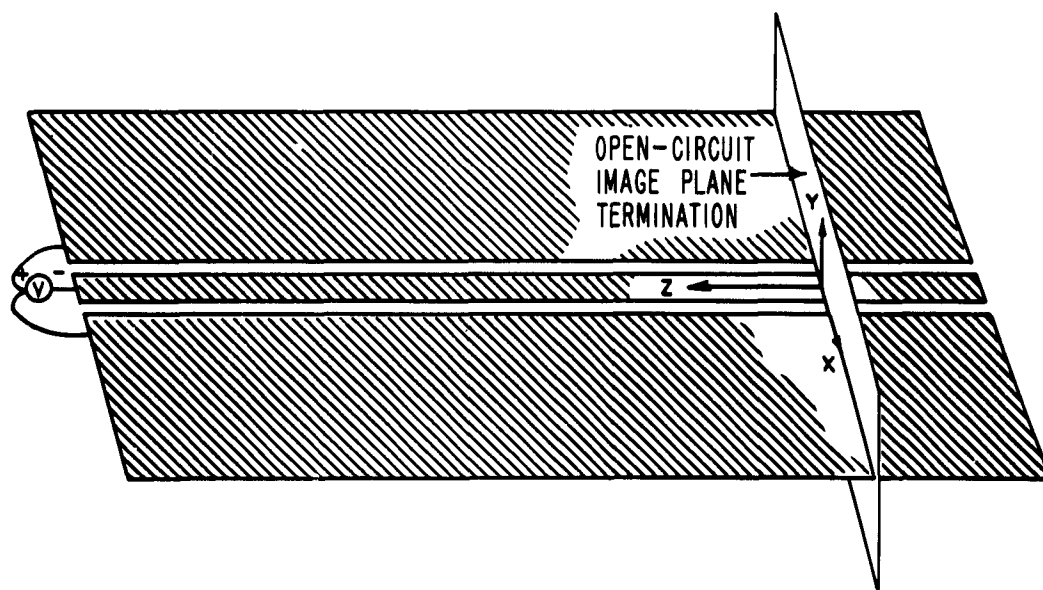
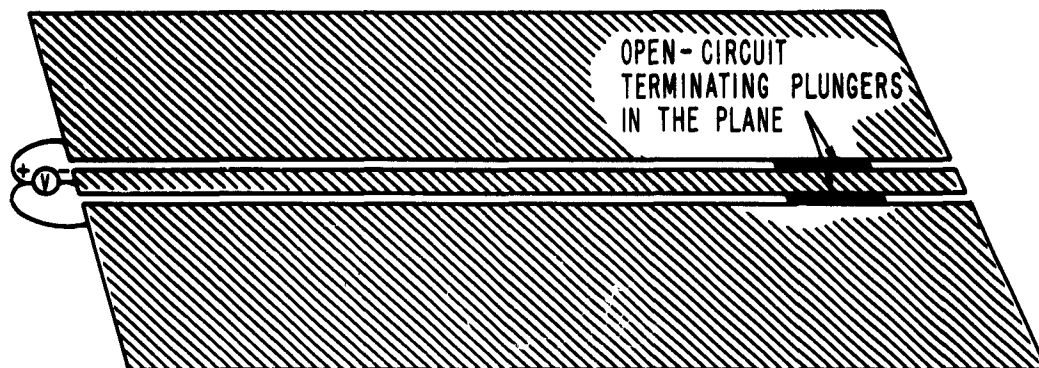
- (a) the effect of a conventional conducting image plane as a termination.

- (b) a practical design of a matched load.
- (c) the effects of a bend-out-of-the-plane on transmission characteristics.

1.2 The Conducting Image Plane as a Termination for the Slot Transmission-Line

In ordinary transmission-line theory it is possible to study the behavior and characteristics of the short-circuited line without end effects if the short circuit is an image plane. No corresponding freedom is possible in the case of the open-circuited termination. As noted by Owyang, the slot transmission-line in the plane is the dual of the two-strip transmission-line, by which is meant that all impedances of the one become corresponding admittances of the other. Therefore, in the case of two slots terminated in a conducting image plane (an open slot line) one may expect a method of analyzing the corresponding open-circuited ordinary transmission-line without end effects; and, indeed, that is the case (Fig. 1.1). The slot transmission-line terminated with metal plungers in the plane has a 0.03λ inductive shift (i. e., towards the termination) of minimums, whereas there is no shift in the case of its termination in a conducting image plane. It is interesting to note the duality between slot and ordinary transmission-lines. On the one hand, the open-circuited ordinary transmission-line is known to have a capacitive shift, and we see here, on the other hand, that the open-circuited slot line has an inductive shift.

With the conducting plate as the image termination on the slot transmission-line the current distribution on the vertical plate was



OPEN-CIRCUIT TERMINATIONS OF SLOT TRANSMISSION-LINE
FIG. 1.1

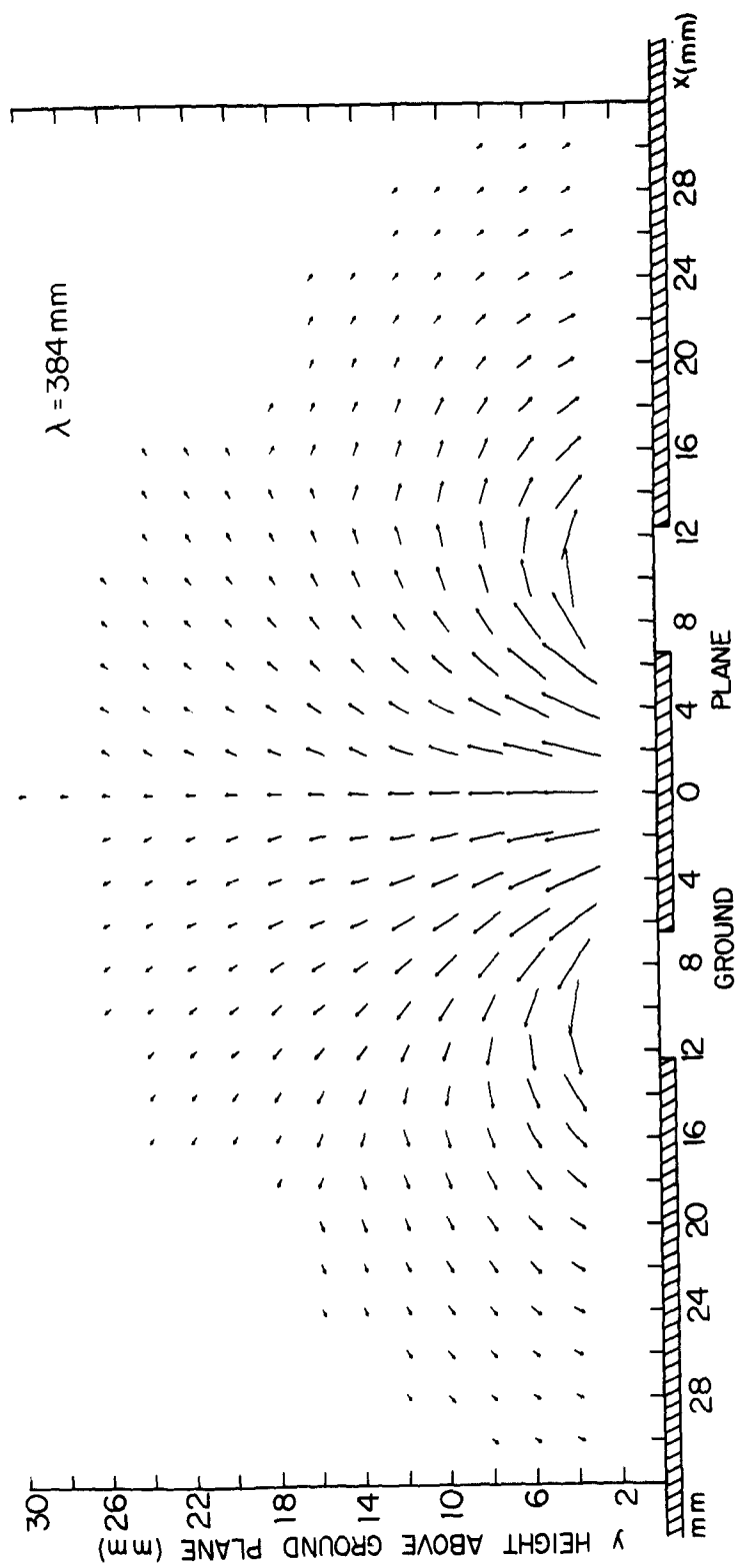
measured as shown in Fig. 1.2. The space vector of current, $J(x, y)$, was determined by orienting a surface type probe of the type in Fig. 1.3 to detect first the x-component then the y-component of $J(x, y)$ in each position. For interest, Fig. 1.4 compares the function $J(0, y)$ and $1/y$ - the $1/y$ variation being the correct theoretical function for cylindrical wires, whereas the slots are of square cross section.

1.3 A Practical Design for a Matched Load for a Slot Transmission-Line

A matched load was built for the slot transmission-line by applying successive coats of Aquadag (colloidal graphite in water) on a styrofoam termination block (Fig. 1.5). A minimum voltage standing-wave ratio of 1.12 was obtained by this method using an impregnated styrofoam block with 69 ohms dc resistance.

1.4 Effects on Transmission Characteristics with a Bend-out-of-the-Plane

The original purpose for designing the matched load for the slot transmission-line was its use in studying effects of bends-out-of-the-plane on transmission characteristics. The horizontal section of line was to be driven, and a tilting section terminated in a matched load could be positioned at angles 0° to 90° out-of-the-plane. The original attempt to measure junction characteristics by observing changes in VSWR in the horizontal line as a function of angle proved futile in that no detectable



PLOT OF NORMALIZED SPACE VECTOR OF CURRENT DENSITY $J(x,y)$ AS A FUNCTION OF POSITION ON THE VERTICAL CONDUCTING IMAGE PLANE

FIG. 1.2



SURFACE TYPE PROBE FOR MEASURING RECTANGULAR COMPONENTS OF $J(x,y)$

FIG. I.3

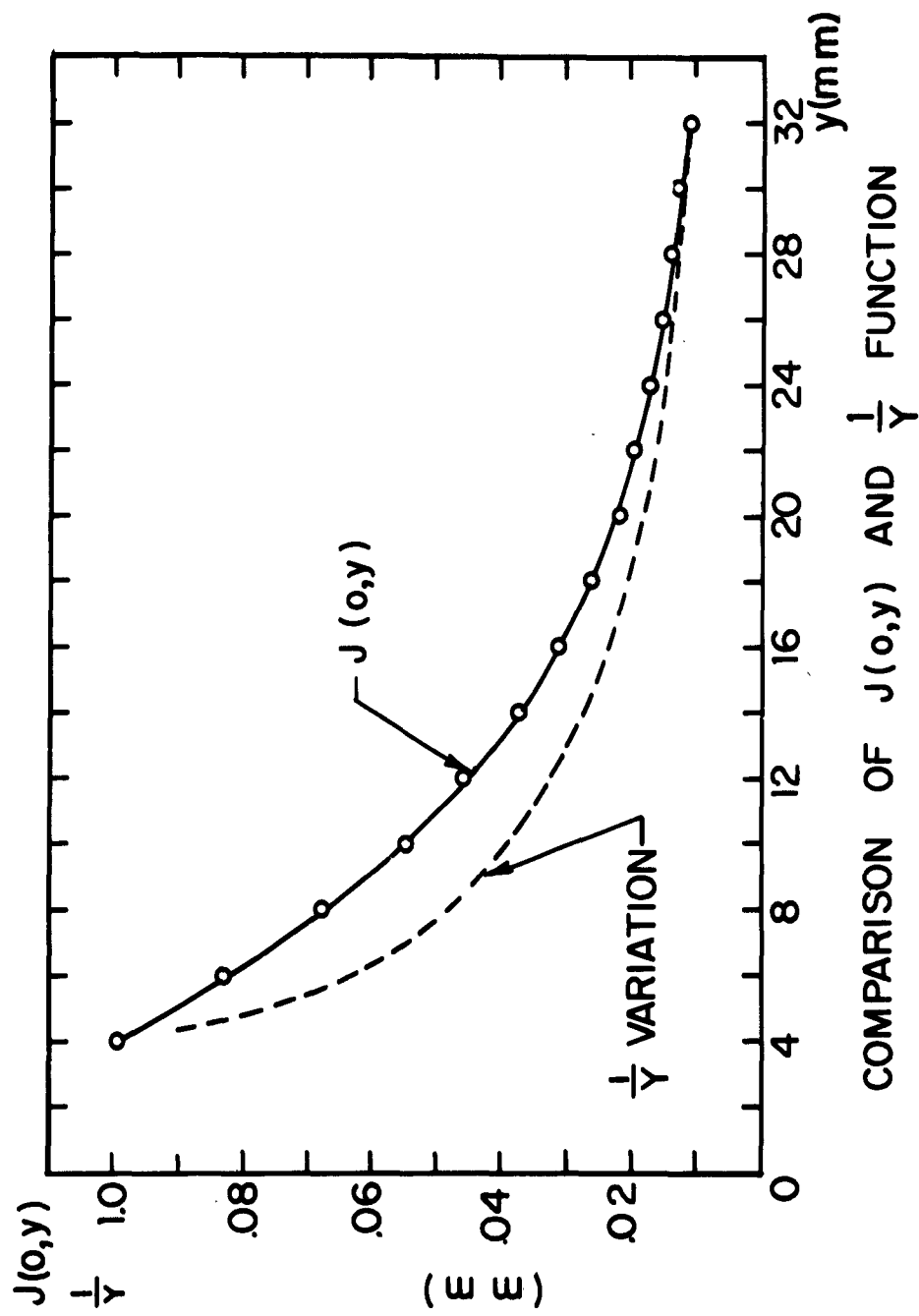
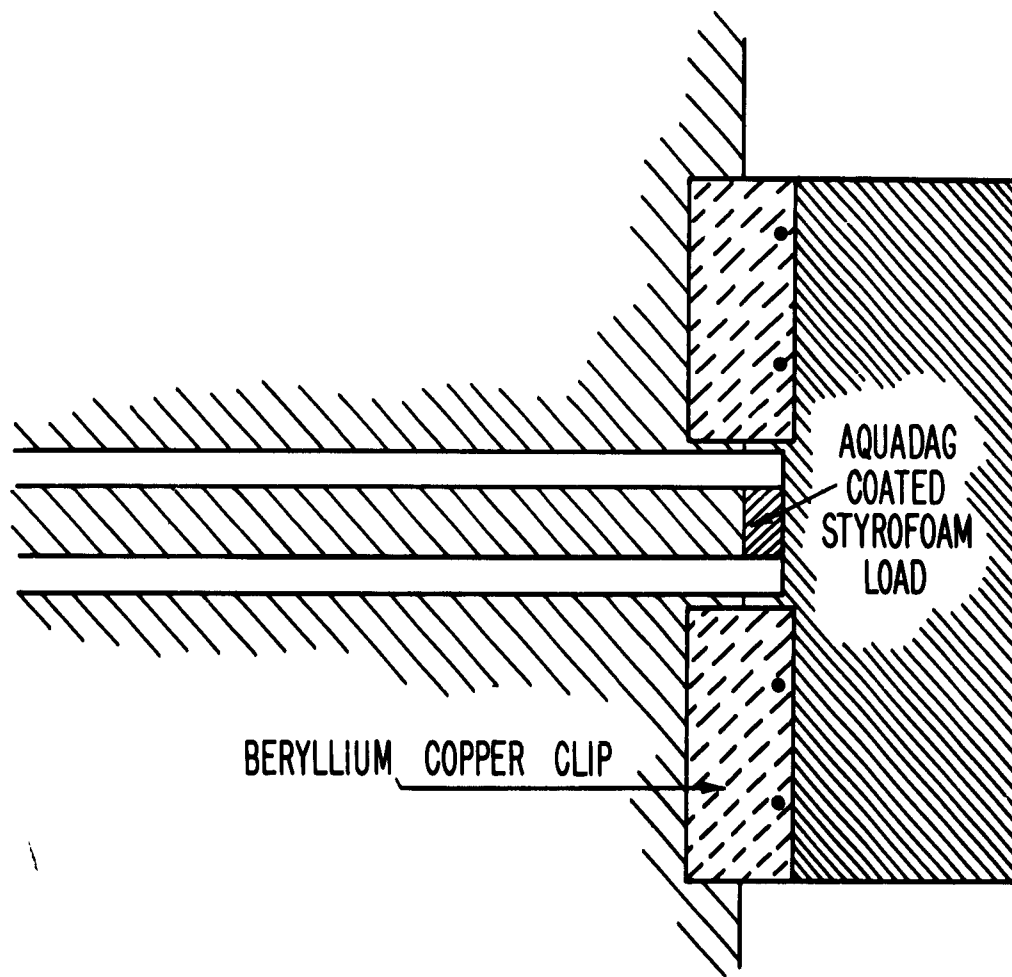


FIG. 1.4



TOP VIEW SLOT TRANSMISSION-LINE WITH MATCHED LOAD

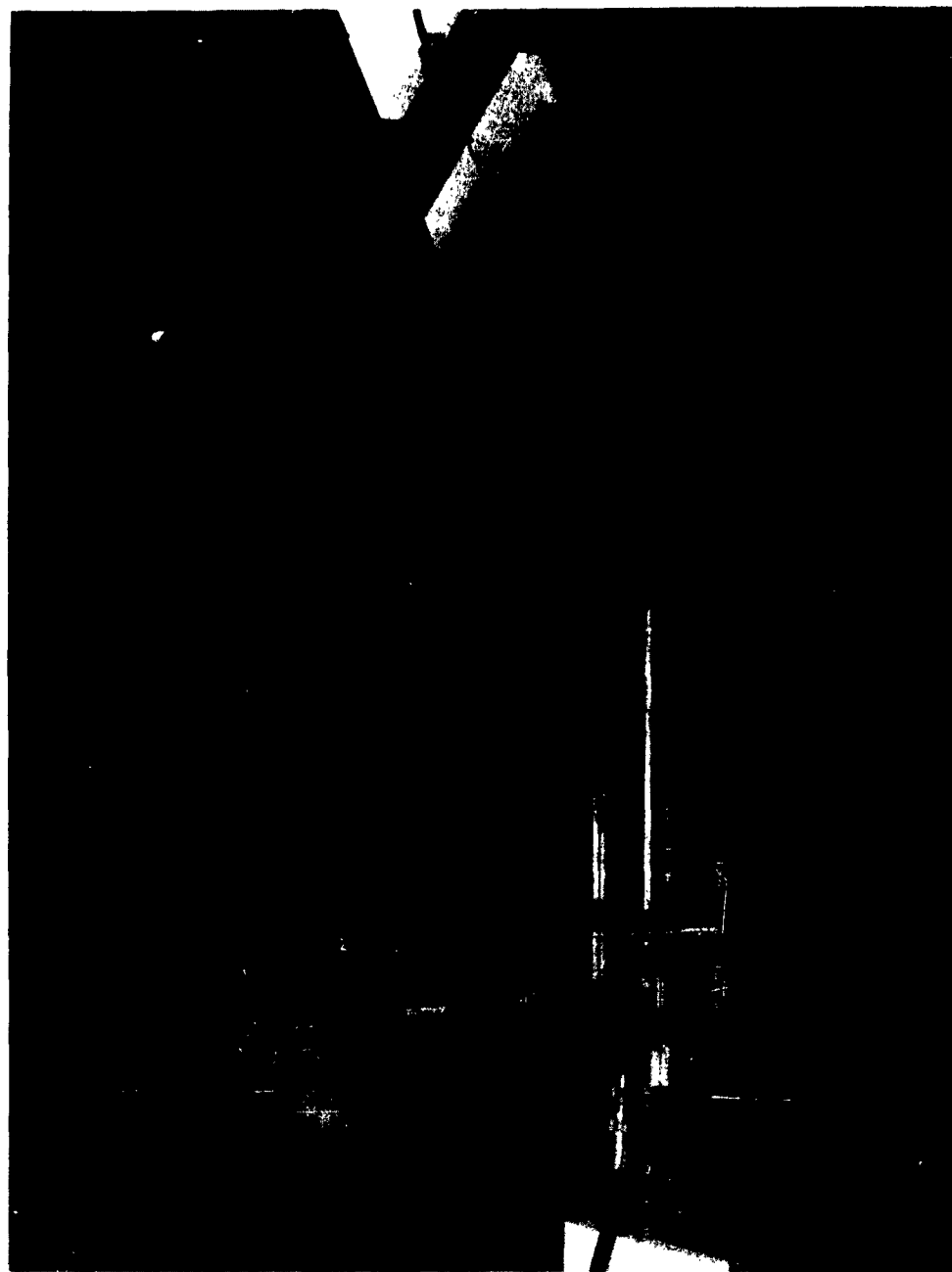
FIG. 1.5

change in VSWR occurred even at a bend of 90° . In addition, the level of VSWR readings on the movable line remained unchanged ruling out any significant radiation. As a result of this coarse experiment, a resonant section of line was constructed to measure junction characteristics directly, and in a more sensitive fashion. [2].

In this phase of the study both an ordinary and a slot resonant section were employed for comparing results. In the case of the ordinary transmission-line a bendable strip of cross section equal to that of the slot was positioned at a distance $d/2$ above an image plane (d is the distance between slots)(Fig. 1.6.). A short-circuiting plate terminated each end of the section of line under consideration. A feed probe on the left was positioned very close to the image plane and loosely coupled to the strip and its mirror image. On the right a loop probe was loosely coupled to detect the H field near the short-circuiting plate.

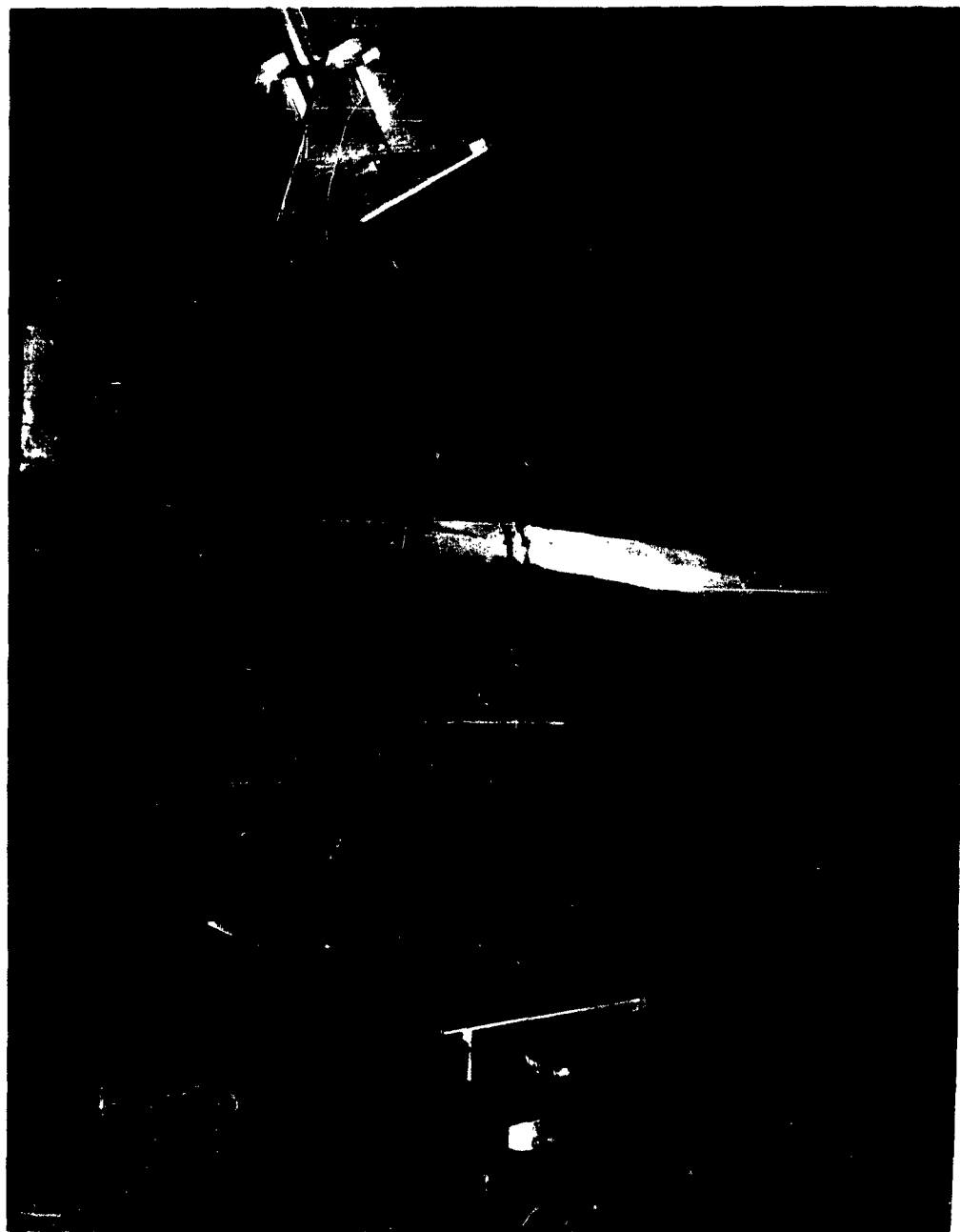
The slot resonant line (Fig. 1.7) was constructed in similar or dual fashion with the one exception that the internal probe system designed by Owyang was used to detect the H field near the terminating plate (Fig. 1.7). In both systems the feed plate was movable.

If we choose the circuits of Fig. 1.8 as possible equivalent transfer circuits for the bend, we may determine L_T , L_T^* , C_T and C_T^* much as King and Tomyasu did for the ordinary transmission-line.[3].The neglect of radiation seems appropriate from the results discussed earlier. We may, for example, detect L_T by positioning the short-circuiting plates $\frac{\lambda}{2}$



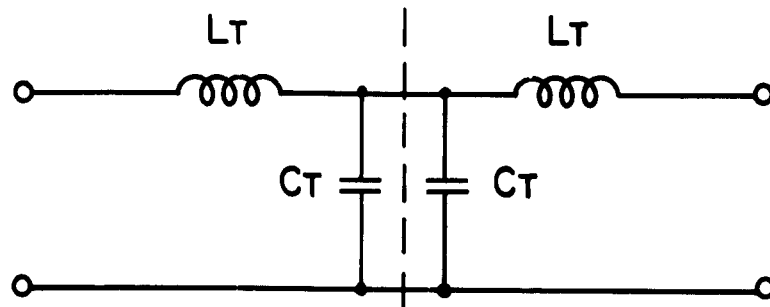
RESONANT SECTION OF ORDINARY STRIP TRANSMISSION - LINE

FIG. 1.6

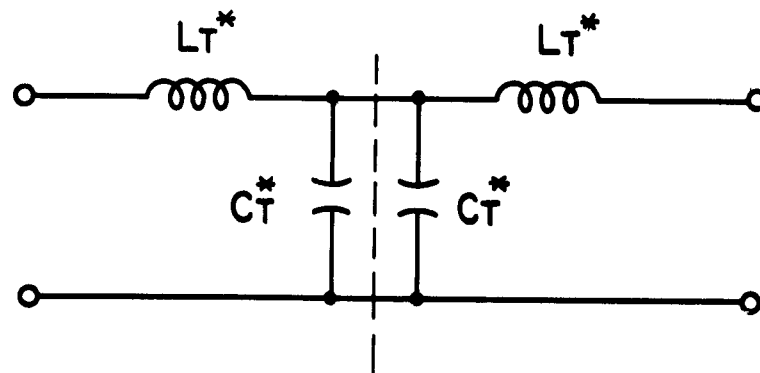


RESONANT SECTION OF SLOT TRANSMISSION-LINE

FIG. 1.7



AN EQUIVALENT TRANSFER CIRCUIT FOR ORDINARY
TRANSMISSION-LINE AT THE BEND



AN EQUIVALENT TRANSFER CIRCUIT FOR SLOT
TRANSMISSION-LINE AT THE BEND

FIG. 1.8

on either side of the bend. In that case, a current maximum and charge minimum will be maintained at the bend, emphasizing the effects of L_T and neglecting those of C_T .

In the experiment it is convenient to measure the distance Δz by which the plate terminations are moved closer together or further apart to achieve a new resonance at a bend angle of θ . This differential distance moved from the original position at $\theta = 0$ is conveniently the normalized L_T/l_0 , C_T/c_0 , L_T^*/l_0^* and C_T^*/c_0^* depending on the case in study.

As a theoretical illustration [4] consider the ordinary line with short circuits positioned $\frac{\lambda}{2}$ on either side of the bend effecting a current maximum and charge minimum at the bend in Fig. 1.9a. The normalized impedance Z_{IN}/z_0 looking either right or left is

$$Z_{IN} = j \tan \beta z \quad (1-1)$$

Z termination = 0.

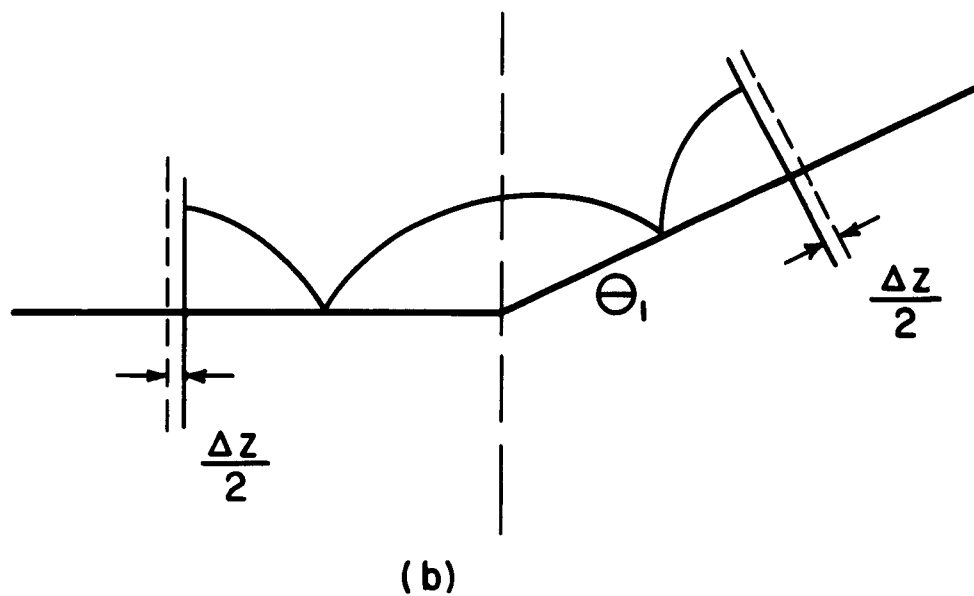
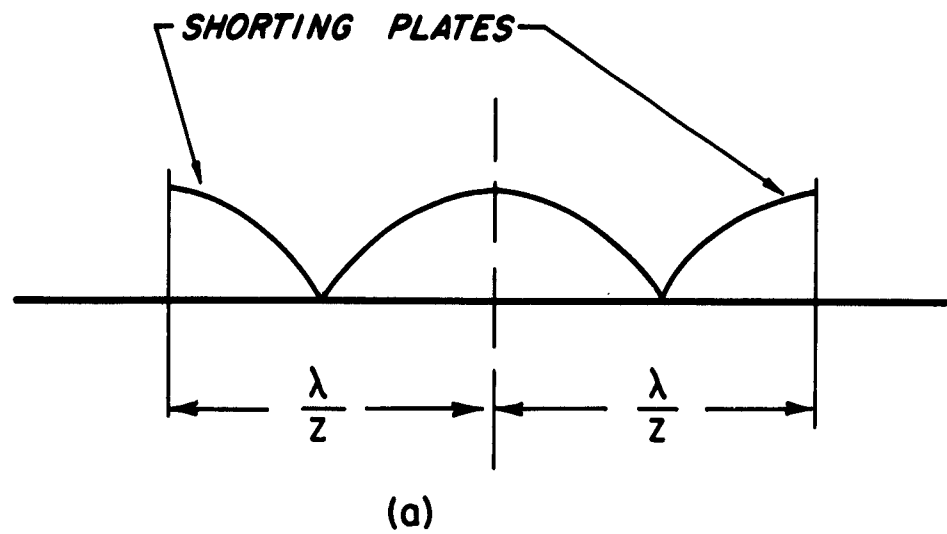
Now in Fig. 1.9b when θ is changed to θ_1 , a new resonance is obtained, say, by moving each image plane toward the bend $\frac{\Delta z}{2}$. The input impedance considering the lengths of line involved into either side is

$$Z_{IN} = j \tan \left\{ \frac{2\pi}{\lambda} \left(\frac{\lambda}{2} - \frac{\Delta z}{2} \right) \right\} \quad (1-2)$$

given a change of impedance of

$$Z_{IN} = -j \tan \frac{\pi \Delta z}{\lambda} \approx -j \frac{\pi \Delta z}{\lambda} \quad (1-3)$$

Since we have achieved resonance in this position ($Z_{IN} = 0$), the bend must have introduced an impedance of $+j \frac{\pi \Delta z}{\lambda}$. Since, in this case, the



RESONANT SECTION OF ORDINARY TRANSMISSION-
LINE IN BENDING EXPERIMENT

FIG. 1.9

equivalent transfer circuit is essentially inductive

$$\frac{\omega L_T}{Z_c} = \frac{\pi \Delta z}{\lambda} \quad (1-4)$$

or

$$\frac{L_T}{l_0} = \frac{\Delta z}{2} \text{ cm.} \quad (1-5)$$

Similarly, in the case of the slot transmission-line with opens positioned at $\frac{\lambda}{2}$

$$Z_{IN}^* = \frac{1}{j \tan \beta z} \quad (1-6)$$

Z^* termination = ∞

which is $\theta = 0$ and $z = \frac{\lambda}{2}$ gives $Z_{IN}^* = \infty$. When θ is changed to θ_1 , a new resonance is obtained by moving the image planes towards the bend a distance $\frac{\Delta z}{2}$ each. The new input impedance Z_{IN}^* considering transmission-line length is now

$$Z_{IN}^* = \frac{1}{j \tan \left\{ \frac{2\pi}{\lambda} \left(\frac{\lambda}{2} - \frac{\Delta z}{2} \right) \right\}} \quad (1-7)$$

giving a change of impedance of

$$Z_{IN}^*_{CHANGE} = \frac{1}{j \tan \frac{\pi \Delta z}{\lambda}} \approx \frac{1}{-j \frac{\pi \Delta z}{\lambda}} \quad (1-8)$$

In order to achieve resonance ($Z_{IN}^* = \infty$ in this case) the impedance $\frac{1}{j \frac{\pi \Delta z}{\lambda}}$ was introduced by the bend. Since the circuit is primarily capacitive, $\frac{C_T^*}{c_0}$ may be determined as follows

$$\frac{\frac{1}{j\omega C_T^*}}{Z_c^*} = \frac{1}{\frac{j\pi \Delta z}{\lambda}} \quad (1-9)$$

and

$$\frac{C_T^*}{c_0} = \frac{\Delta z}{2} \text{ cm.} \quad (1-10)$$

As a practical matter in the experiment, it was not suitable to move both image planes since the maximum total distance moved was less than 0.5 cm. Consequently, only the feed plate was moved and corresponding slight error was introduced. The magnitude of this error is obviously small, since even in the maximum shift of 0.5 cm, the ratio at the bend was still 40 dB.

For interest, Fig. 1.10 displays an experimental resonance curve for the slot line. In this experiment $\theta = 0$ and the feed plate was moved. The internal probe positioned near the fixed plate detected a signal proportional to the square of the current along the outer edge of one slot. The major results of this phase of experimental work are presented in Figs. 1.11 and 1.12. The theoretical curves were accomplished by applying the approximate theory of Tomiyasu and King to a transmission-line with a square cross section. In all instances the differential distances moved to achieve resonance are corrected for the increase in mean length from 0 to $\frac{\pi a}{4}$ (a is the slot or strip thickness) as the transmission-line was bent from 0° to 90° .

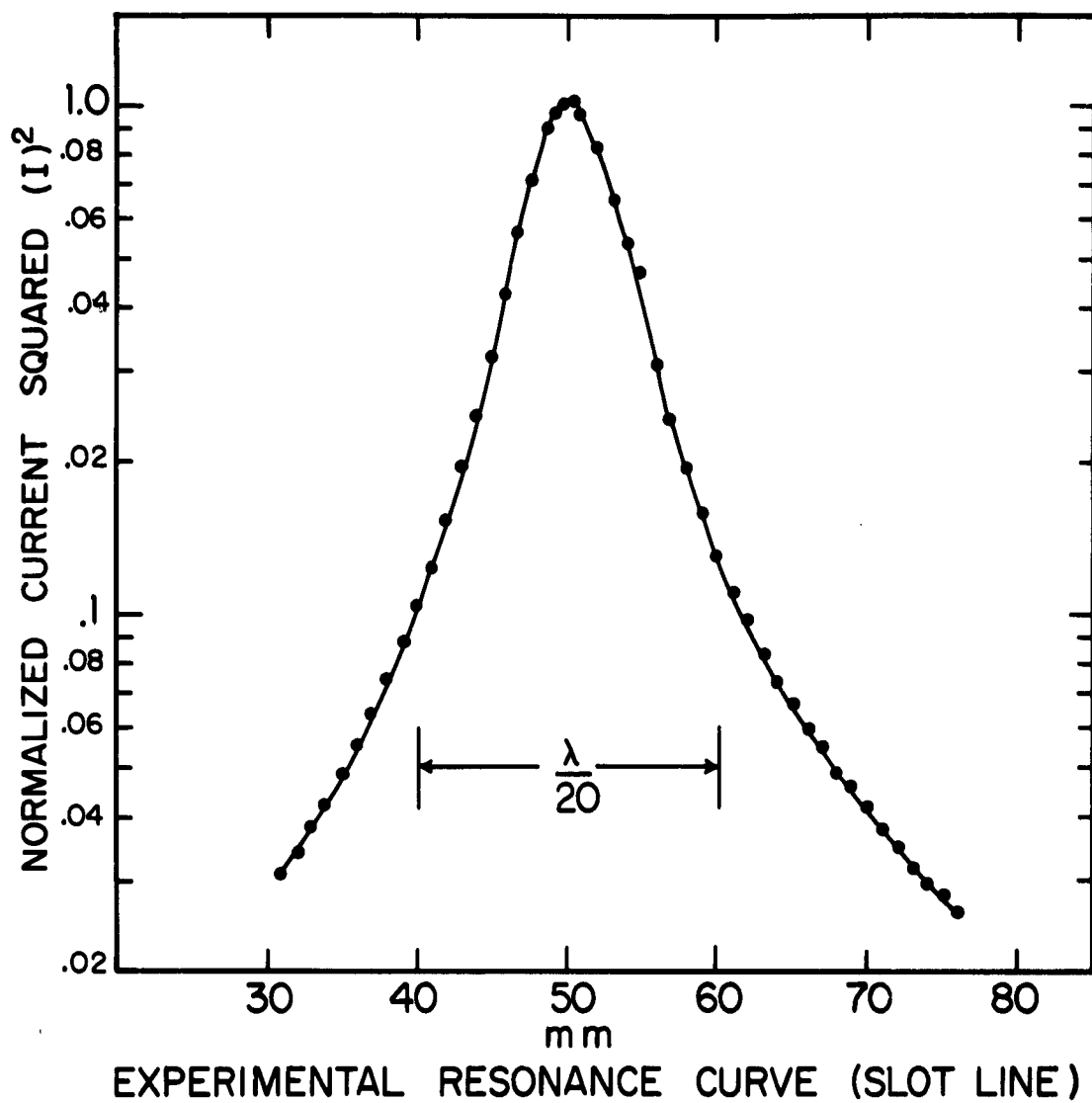
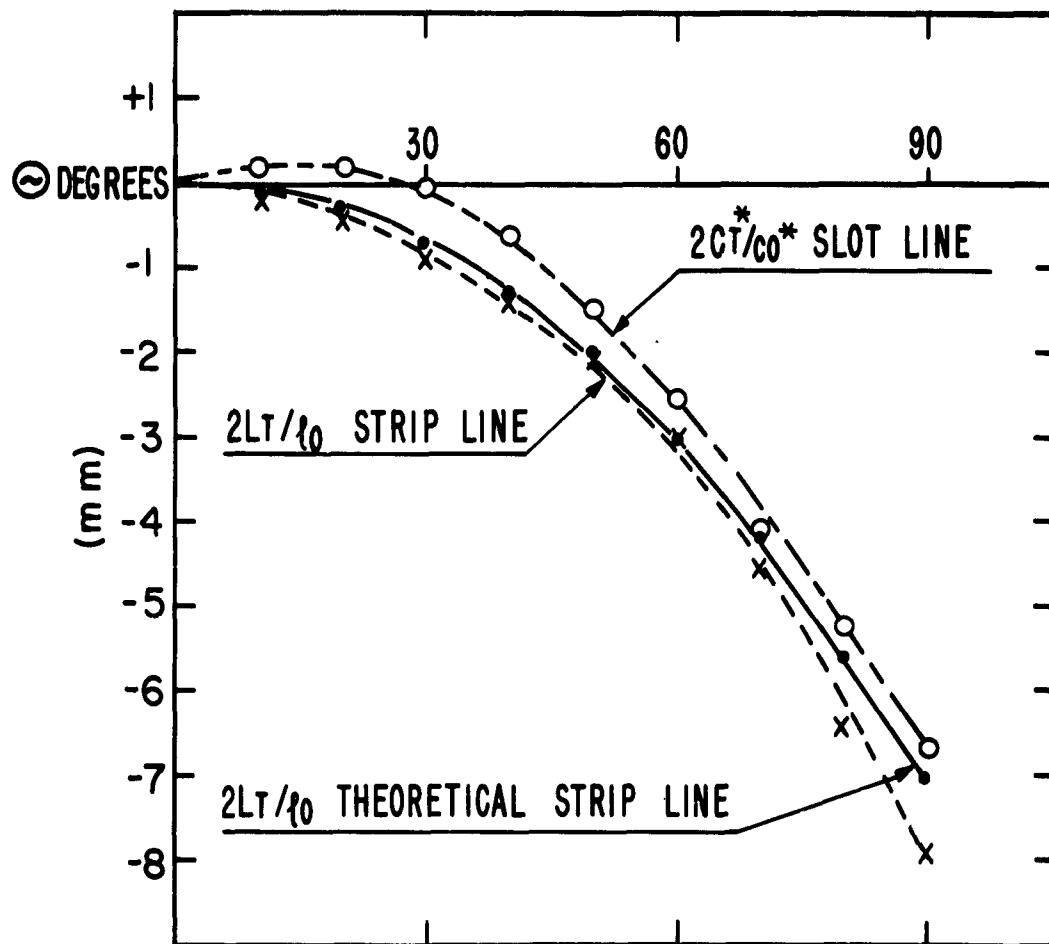
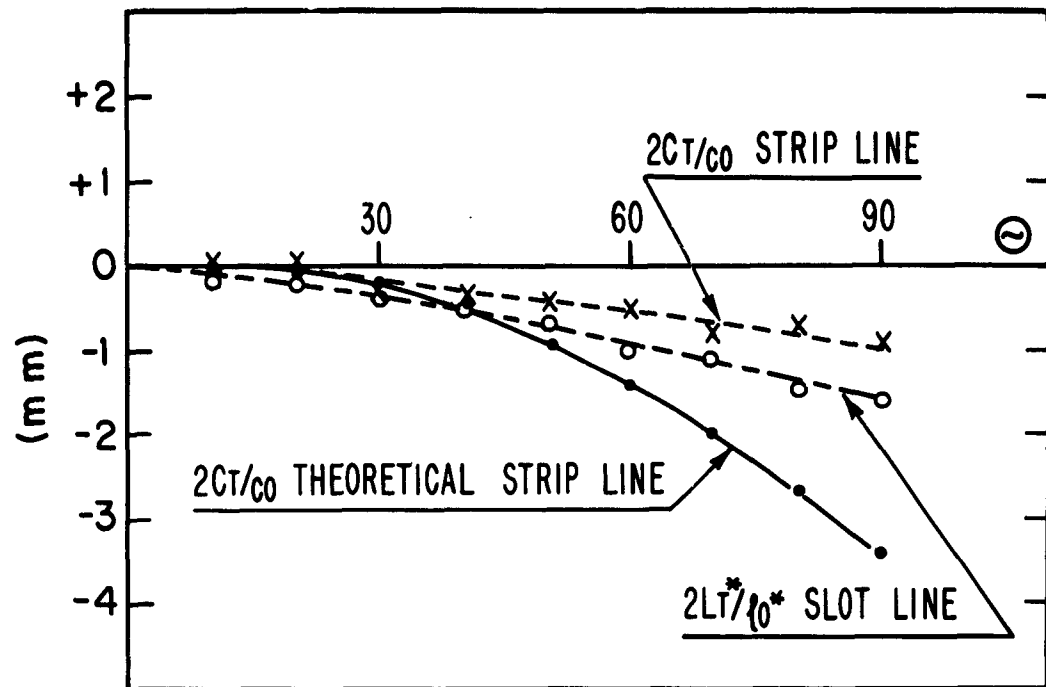


FIG. 1.10



PLOT OF $2LT/l_0$ THEORETICAL AND EXPERIMENTAL RESULTS FOR STRIP LINE, $2CT/co^*$ EXPERIMENTAL RESULT FOR SLOTTED LINE AS A FUNCTION OF Θ , ANGLE OF BEND


FIG. 1.11




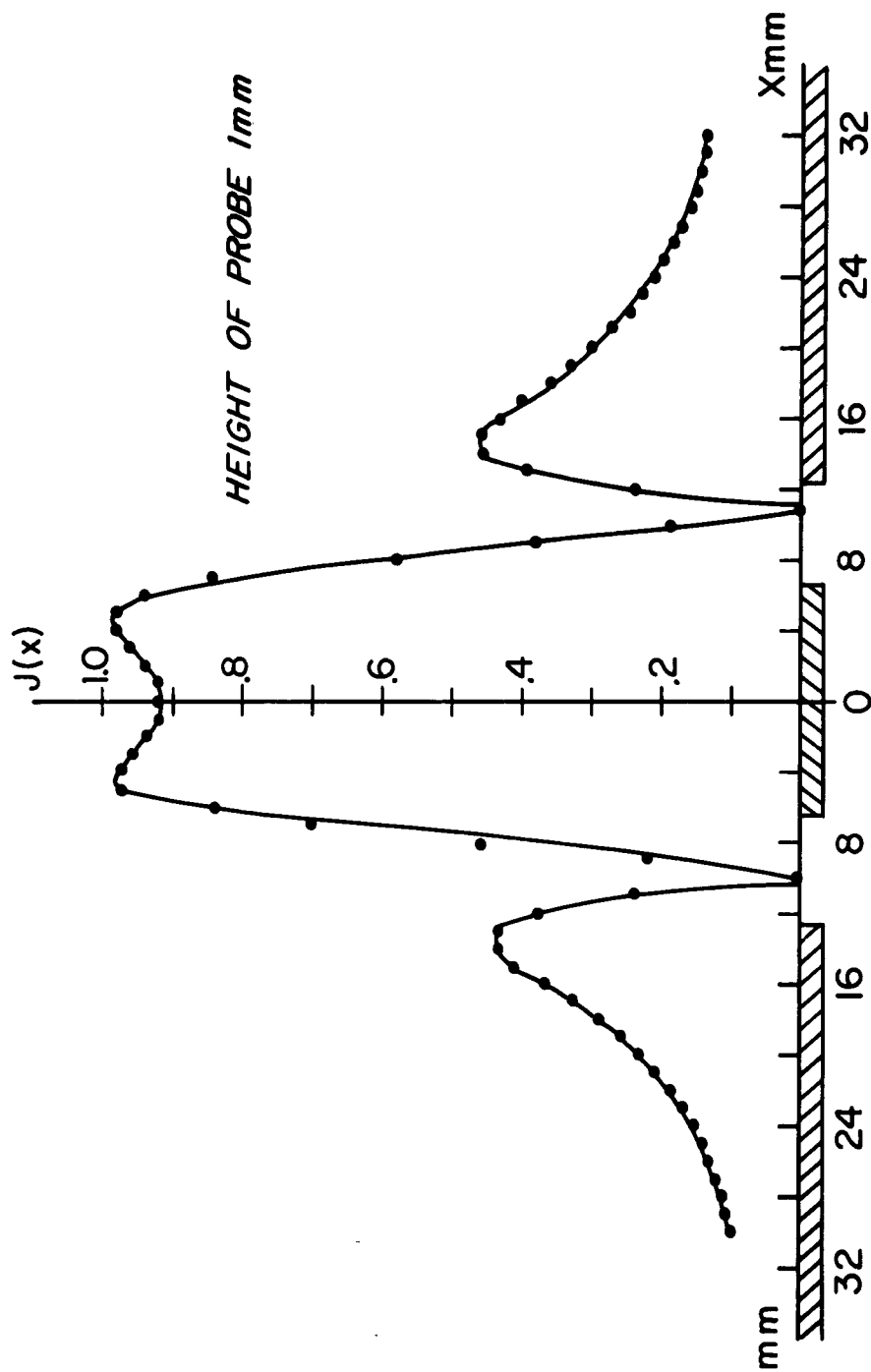
PLOT OF $2CT/c_0$ THEORETICAL AND EXPERIMENTAL RESULTS FOR STRIP LINE AND $2LT/l_0^*$ EXPERIMENTAL RESULT FOR SLOT LINE AS A FUNCTION OF Θ , ANGLE OF BEND

FIG. 1.12

1.5 Conclusion



The results of this experiment to show the effects of bends out-of-the-plane are, on the one hand, somewhat surprising and, on the other, somewhat expected. Babinet's principle offers a method of solving complementary or dual problems but only if the elements are in the plane. Electromagnetic fields resulting from dual sources or elements are synthesized using symmetrical and antisymmetrical fields about a planar surface. No corresponding analogy may be drawn for fields about non-planar configurations.  On the other hand, if the problem is considered as a transmission-line problem, a study in local effects is in order. If we consider Fig. 1.13, a plot of current density $J(x)$ as a function of position measured normal to the slots, we observe that the current outboard of the slots is generally confined to an area in width of about $40 \text{ mm} (\lambda/10)$ on either side of the slots. As a consequence, there is no reason to expect that the slot transmission-line will not behave as its dual does around bends and curves. In fact, with such a confined distribution of current, it may be convenient to consider the slot transmission-line as a hybrid three-wire line with current flowing down the center conductor between the slots and back along the sides outboard of the slots. In addition to this viewpoint, it might be well to consider a four-wire line representation with two streams of current concentrated near the outer edges of the inner conductor flowing down and two return streams flowing back along the outboard edges of the slot.



PLOT OF NORMALIZED CURRENT DENSITY $J(x)$ AS A FUNCTION OF POSITION MEASURED NORMAL TO TRANSMISSION LINE

FIG. 1.13

References

1. G. H. Owyang, "The Slot Transmission-Line and The Slot Antenna," Ph.D. Thesis, Harvard University, 1959.
2. Ronold W. P. King, "Transmission-Line Theory," McGraw-Hill, New York, p. 148-150, 1955.
3. Ronold W. P. King and Kiyo Tomiyasu, "Terminal Impedance and Generalized Two-Wire Theory", Cruft Laboratory Technical Report No. 74, Harvard University, April 15, 1945.
4. Ronold W. P. King, "Transmission-Line Theory", McGraw-Hill, New York, p. 133-135, 1955.

Acknowledgment

The author is greatly indebted to Professor Ronold W. P. King for suggestion of this problem and his timely encouragement in its pursuit.

To Charles Sampson my sincere appreciation for continual excellence in his machinist and technician support.

Activity Supply Officer
Building 1604, Charles Wood Area
Fort Monmouth, New Jersey (10)
Attn: Director of Research

Commanding Officer
Office of Naval Research
Naval Research Building
Washington 25, D. C. (25)
Attn: Post Office

Armed Services
Technical Information Agency
Arlington Hall Station (10)
Arlington 12, Virginia
Attn: TSPDS

The Director
Naval Research Laboratory
Washington 25, D. C. (10)
Attn: Technical Information Office

Commander, AFRL
AFRL, AFRL, AFRL
Lawrence G. Hanson Field (4)
Bedford, Massachusetts
Attn: Electronics Research Directorate

Commanding General
Air Research and Development Command
P. O. Box 199 (3)
Baltimore 3, Maryland
Attn: RDT&D

Chief of Naval Research
Department of the Navy (2)
Washington 25, D. C.
Attn: Dr. A. Hanson, Code 417

Chief of Naval Research
Department of the Navy (2)
Washington 25, D. C.
Attn: Code 417

Commanding Officer
Office of Naval Research
415 Summer Street (2)
Boston, Massachusetts

Chief, Bureau of Ships
Department of the Navy (2)
Washington 25, D. C.
Attn: Code 818

Director, Air University
Library (2)
Maxwell Air Force Base
Alabama

Chief of Naval Research
Department of the Navy
Washington 25, D. C.
Attn: Code 417

Commanding Officer
Office of Naval Research
415 Summer Street
Boston, Massachusetts

Commanding Officer
Office of Naval Research
John George Library Building
55 West Randolph Street
Chicago 1, Illinois

Commanding Officer
Office of Naval Research
36 Broadway
New York 13, New York

Commanding Officer
Office of Naval Research
1530 East Ocean Street
Pasadena, California

Commanding Officer
Office of Naval Research
1030 Garry Street
San Francisco 9, California

Head, Document Section
Technical Information Division
Naval Research Laboratory
Washington 25, D. C.

Martin A. Carlson
Magazine Branch, Code 1440
Build Branch Division
Naval Research Laboratory
Washington 25, D. C.

Commanding Officer
U. S. H. Air Development Center
Jamaica, Pennsylvania
Attn: NADC Library

Commander
U. S. H. Air Development Center
Jamaica, Pennsylvania
Attn: AASL

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D. C.
Attn: RI-1

Engineering Library
Central
San Diego 12, California

Dr. John E. Phipps
Applied Physics and Ferrite Devices
Gerry Microwave Electronics Co.
P. O. Box 1532
Gainesville, Florida

Engineering Library
Gerry Microwave Electronics Co.
Gainesville, Florida

Dr. Lajos Rinal
Research Division
Raytheon Company
Waltham 54, Massachusetts

Elizabeth Webb, Librarian
Raytheon Company
33 Bryan Street
Waltham 54, Massachusetts

Report Libraries
Electronic Electric Products Inc.
Electronic Systems Division
160 First Avenue
Waltham, Massachusetts

Document Control Center
Wayland Library
Wayland Manufacturing Co.
Wayland, Massachusetts

J. E. Goldman
Scientific Laboratory
Ford Motor Company
Engineering Staff
P. O. Box 1455
Dearborn, Michigan

Charles C. H. Tang
Bell Telephone Lab.
Murray Hill, New Jersey

Librarian
RCA Laboratories
Princeton, New Jersey

Dr. A. Smith
Princeton, New Jersey

Commander (2)
U. S. Naval Electronics Lab.
San Diego, California

Commanding General, BCRW
Naval Air Development Center
Griffith Air Force Base (2)
Rome, New York

Commanding General
Air Research and Development Command
P. O. Box 199 (1)
Baltimore, Maryland
Attn: RDT&D

Commander
Air Force Cambridge Research Lab.
Lawrence G. Hanson Field (2)
Bedford, Massachusetts
Attn: CROTLA

Commander
Wright Air Development Center
Wright Patterson Air Force Base
Ohio (2)
Attn: WGLRA Library

National Security Agency
Physical Sciences Division (2)
Fort George Meade, Maryland
Attn: Dr. Alvin Mueller

Associate Prof. A. Kaprielian
Department of Electrical Engineering
University of Southern California
University Park
Los Angeles 1, California

Assistant Secretary of Defense
Research and Development Board
Department of Defense
Washington 25, D. C.

Chief of Naval Operations
Department of the Navy
Washington 25, D. C.
Attn: Op-23

Chief of Naval Operations
Department of the Navy
Washington 25, D. C.
Attn: Op-23

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D. C.
Attn: RI-4

Technical Library
U. S. Naval Proving Ground
 Dahlgren, Virginia

Director
Naval Ordnance Laboratory
White Oak, Maryland

Librarian
U. S. Naval Post Graduate School
Monterey, California

Air Force Office of Scientific Research
Air Research and Development Command
Washington 25, D. C.
Attn: S&V, Physics Division

Commanding General
Naval Air Development Center
Griffith Air Force Base
Rome, New York
Attn: RCRBC-VC

Commanding General
Naval Air Development Center
Griffith Air Force Base
Rome, New York
Attn: RCR

Commander
Air Force Cambridge Research Center
128 Albany Street
Cambridge 39, Massachusetts
Attn: CRRL

Commander
Air Force Cambridge Research Center
128 Albany Street
Cambridge 39, Massachusetts
Attn: CRRL

Commander
AF Cambridge Research Laboratories
Lawrence G. Hanson Field
Bedford, Massachusetts
Attn: Dr. Hollingsworth

Wright Air Development Center
Wright Patterson Air Force Base
Ohio
Attn: WCRB

Sandia Corporation
Org. 1434, Sandia Base
Albuquerque, New Mexico
Attn: Dr. C. W. Harrison, Jr.

Sandia Corporation
Sandia Base
Albuquerque, New Mexico
Attn: Library Division (151-1)

Mr. Robert Turvey
General Electric Company
Advanced Electronics Center
Cornell University
Ithaca, New York

Library
Airborne Instruments Lab.
Ft. Belvoir, Long Island, New York

Secretary, Working Group
Semiconductor Devices
344 Broadway, 36 Floor
New York 13, New York
Attn: ASST

Mobile Research Laboratories
Electronic Metallurgical Company
Box 100, Hagen Field, New York
Attn: Mr. J. J. Glavin

Librarian
General Electric Research Lab.
P. O. Box 1088
Schenectady, New York

Westinghouse Electric Corp.
Research Laboratories
Bruck Road, Churchill Park
Pittsburgh 39, Pennsylvania

Prof. O. E. N. Rydbeck
P. O. Box 144
Salmon, New Jersey

Dr. Melvin W. Arneson
611 San Geronimo Street
Princeton, New Jersey

Librarian
Airborne Instruments
Mineola, New York

Commander
Wright Air Development Center
Wright Patterson Air Force Base
Ohio
Attn: WCRB

Commander
Air Force Institute of Technology
Wright Patterson Air Force Base
Ohio
Attn: MGLI Library

AF Special Weapons Center
Hilland Air Force Base
Altamonte, New Mexico
Attn: SWCS

Headquarters
AF Missile Test Center
MS-118, ABSC
Patrick Air Force Base
Florida

U. S. Coast Guard
1308 B Street, N. W.
Washington 25, D. C.
Attn: RSB

M. A. Krievanich, Chief
Systems Component Branch
Electronic Warfare Division
Signal Corps Agency
Wright Patterson Air Force Base
New Mexico

Mr. A. D. Bedrosian
Signal Corps Liaison Office
Mass. Institute of Technology
Building 24, Room 131
Cambridge 39, Massachusetts

Chief, European Office
ABSC Command
Ball Building
50 Rue Ravenstein
Brussels, Belgium

Dr. J. Anton Molnar
Ordnance Materials Res. Office
Watervliet Arsenal
Watervliet, Massachusetts

AFRL Office
AFRL, AFRL, AFRL
Arlington Hall Station
Arlington 12, Virginia

Standard Research Institute
Documents Center
Mesa Park, California
Attn: Mary Lee Fields

Dr. C. H. Pappas
Dep. of Electrical Engineering
California Institute of Technology
Pasadena, California

Standard Electronics Lab.
Standard University
Standard, California
Attn: Document Library

Department of Electrical Engineering
Yale University
New Haven, Connecticut

Librarian
Johns Hopkins University
1115 St. Paul Street
Baltimore 3, Maryland

Radiation Laboratory
Johns Hopkins University
1115 St. Paul Street
Baltimore 3, Maryland

Director, Lincoln Laboratory
Mass. Institute of Technology
Bedford, Massachusetts

Mr. John Novitt
Document Room
Research Lab. of Electronics
Mass. Institute of Technology
Cambridge 39, Massachusetts

Professor A. Van Hapel
Mass. Institute of Technology
Lab. for Ionization Research
Cambridge 39, Massachusetts

Library, Room A 225
Lincoln Laboratory
P. O. Box 13
Lexington 73, Massachusetts

K. M. Siegel, Head
Theory and Analysis Department
Willow Run Laboratories
University of Michigan
Willow Run Airport
Ypsilanti, Michigan

Martin A. Carlson, Head
Paramagnetic Section
Department of Physics
Washington University
St. Louis, Missouri

Dr. Reiner Bruesch, Jr.
Ordnance Materials
Research Laboratory
Watervliet Arsenal
Watervliet, Massachusetts

Mr. A. Saha
Nimeji Technical College
Nimeji, Japan

Electronics Research Laboratory
Division of Electrical Engineering
University of California
Berkeley 4, California
Attn: Librarian

Johns Hopkins University
John and Charles Street
Baltimore 18, Maryland
Attn: Mr. J. O. Arman

Librarian
Physics Department
Amherst College
Amherst, Massachusetts
Attn: Mr. Rimes

Professor L. Low
Department of Physics
University of Minnesota
Minneapolis, Minnesota

Michigan State College
Department of Mathematics
East Lansing, Michigan

Microscopic Research Institute
Polytechnic Institute of Brooklyn
33 Johnson Street
Brooklyn, New York

Dr. W. M. Walsh
Bell Telephone Lab., Inc.
Murray Hill, New Jersey

Librarian
IBM Watson Laboratories
415 West 118th Street
New York 27, New York

SOLID STATE ONLY

Librarian
National Bureau of Standards Library
Room 361, Northwest Building
Washington 25, D. C.

U. S. Department of Commerce
National Bureau of Standards
Boulder, Colorado

Dr. Earl Cohen
National Security Agency
Physical Sciences Division
Fort George Meade, Maryland

Dr. H. Campaig
National Security Agency
Physical Sciences Division
Fort George Meade, Maryland

Chung Hing University
Electrical Engineering Department
Taipei, Taiwan
Republic of China
Attn: Professor Chao-Hsi Chen
Head, Eng. Department

Mr. D. S. Jones
Department of Mathematics
Univ. College of St. Andrews
Keele, Staffordshire, England

Professor Paul Sami Moe
Oakland City University
Dept. of Radiological Science
13 West 10th Street
Omaha, Nebraska

Donald C. Simon
Dept. of Electrical Eng.
University of Arizona
Tucson 22, Arizona

Professor Jerome R. Singer
Div. of Electrical Engineering
University of California
Berkeley 4, California

Professor Charles Noel
Department of Physics
University of California
Berkeley 4, California

Seriale Library
Stanford University
Walton, Massachusetts

Professor M. G. Becher
School of Electrical Engineering
Cornell University
Ithaca, New York

Library, College of Engineering
University Heights Library
University Heights, Ohio
New York University
New York 25, New York

E. A. Chapman, Librarian
Case Institute of Technology
Ames Hall
Troy, New York

Robert Plimley
Department of Engineering
Case Institute of Technology
Cleveland 6, Ohio

Dept. of Electrical Engineering
Case Institute of Technology
University Circle
Cleveland 6, Ohio
Attn: S. Smith, Head

Dr. C. J. Fallick
Bell Telephone Lab.
Columbia, Ohio
Attn: Electrical Engineering Division

Librarian
Engineering Library
Brown University
Providence, Rhode Island

Professor A. W. Spitzer
Dept. of Electrical Engineering
University of Texas
Austin 11, Texas

Mr. William Way
Research Laboratories
Teaser Instruments Corp.
140 Chicago Boulevard
Hollywood 24, California

Professor R. B. Norberg
Department of Physics
Washington University
St. Louis, Missouri

Microscopic Research Institute
Polytechnic Institute of Brooklyn
33 Johnson Street
Brooklyn, New York
Attn: Librarian

Dr. Sidney Shapiro
Prime R. Lind, Inc.
11 Ames Park
Cambridge 44, Massachusetts

Dr. Shun Fong
Lincoln Laboratories
Box 13
Lexington, Massachusetts

Mr. William H. Pym
Rensselaer Polytechnic Institute
100 A Street
Troy, New York

Dr. Edward W. Gorden
1406 Vanvoron Avenue
St. Louis, Missouri

Dr. W. M. Walsh
Bell Telephone Lab., Inc.
Murray Hill, New Jersey

Librarian
IBM Watson Laboratories
415 West 118th Street
New York 27, New York

ELECTROMAGNETIC RADIATION ONLY

Mr. L. E. Swartz, Jr.
Building 18, Room 1417
Hughes Aircraft Laboratories
Culver City, California

Professor O. E. N. Rydbeck
P. O. Box 144
Salmon, New Jersey